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Digital interlooping: 3D printing of weft-knitted textile-based tubular structures using selective laser sintering of nylon powder

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ABSTRACT
This paper discusses the materialisation of 3D printed textile-based tubular forms that make use of knit's primary structures. The 3D printed forms explore both single-face and double-face weft knit structures at various sizes. 3D printing is a form of digital additive manufacturing whereby the building up of layers of material creates objects. The selective laser sintering process (SLS) uses a laser beam to sinter powdered material to create objects. This paper builds upon previous research into 3D printed textile-based structures exploring the use of SLS of Nylon powder to create flexible weft knitted structures. The results show the potential to print flexible, tubular textile-based structures at various scales that exhibit the properties of traditional knitted textile structures along with the mechanical properties of the material used to print with. The conclusion highlights the potential future development and application of such pieces within apparel-related industries.

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1. Introduction

3D printing is an emergent technology which when combined with established textile processes offers the opportunity for a new method of textile production. By replicating the structures of knit through the use of 3D computer-aided design (CAD), it is possible to 3D print knit-based structures. Traditional knitted structures are formed by the interlooping of a continuous thread to create symmetrical loops which create the structure. These loops can be extended in different directions giving knitted structures their inherent stretch and elasticity. By 3D printing knit-based structures it's possible to embed knit's inherent properties of stretch and flexibility, whilst exploiting the mechanical properties of the material used to print with.

The motivation for this research is that to date, previous published research has explored the production of non-continuous, linked geometries to create flexible 3D printed 'textile' material. This research paper addresses a gap in the literature by exploring the 'continuous fibre type geometry' (Bingham et al., 2004) of the 3D printed knit structure and its subsequent effect on material performance. This 'material proposal' (Karana, Barati, Rognoli, & Zeeuw van der Laan, 2015) is explored in synthesis with knit's inherent properties of stretch and flexibility an aspect currently underdeveloped in the testing of 3D printed structures.

This study focuses on testing both single-face (plain) and double-face (interlock) weft knitted tubular structures. The 3D printed knit structures are evaluated in terms of their ability to be compressed and extended, alongside their stretch capabilities and overall flexibility. This research is speculative in nature however, it is anticipated that the results could be utilised within various technical textiles sectors such as sportswear and healthcare.

2. Literature review

2.1. Multiple assemblies/linked geometries

There has been an increased interest in exploring the possibilities of 3D printing flexible textile structures over the past 10 years as demonstrated by the increasing number of research articles published in this field. Most of the 3D printed textiles research projects to date have achieved the desired flexibility through 'discontinuous interlinked structures' (Crookston, Long, Bingham, & Hague, 2007) these structures are often called multiple assemblies as they consist of separate parts (Hopkinson, Hague & Dickens, 2006). A notable example of such

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multiple assembly is Evenhuis and Kyttanen's 3D printed chainmail fashion pieces for Freedom of Creation. These fashion pieces utilise traditional chain mail logic in the form of interlinking closed loops and a variety of other closed interlinking geometries. In terms of flexibility, the textile can be said to articulate if we define articulate as having joints or jointed segments. Rather than stretching the textile has the ability to extend due to movement within the loops.

Following Evenhuis and Kyttanen there have been numerous projects exploring variations of the interlinking chainmail structure. Borhani and Kalanatar (2014) have collaborated with the DREAMS Lab at Virginia Tech Institute on the 'Flexible Textile Structures' research project investigating printed fabrics. Their main aim being to design a 3D printed fabric that has both flexibility and rigidity. They describe the fabric as being 'easily manipulated into a fixed shape due to interference among the links of the printed textile' (Borhani & Kalanatar, 2014). As with Evenhuis and Kyttanen's example, this flexibility can be described as articulation in that rigid components are connected at movable joints.

Developing on from the chainmail logic several designers have explored the interlinking closed loop geometry as a flexible base structure to apply surface geometry. Notably Tom Mallinson (2014) of London based 3D print bureau Digits 2 Widgets has created a series of printed 'textile swatches' that utilise various surface shapes including geometric squares and hemispheres alongside more organic petal and leaves forms. The pieces exhibit flexibility and drapability due to the interlocking linked looped base structure.

A more recent example is Bingham's (2016) '3D Fashion' research project based at Loughborough University in collaboration with the Yeh fashion Group. The aim of this research is to create, 'ready-to-wear net-shaped garments directly from raw material in a single manufacturing operation' (Bingham, 2016). Again, flexibility is achieved through interlinked closed geometries.

2.2. Continuous interlooping geometry

The other method explored by designers to create flexible 3D printed textile structures is through the use of 'continuous fibre type geometry' (Crookston et al., 2007). Felicia Davis (2012) experimental research explores the possibilities of digitally modelling the plain knit stitch to 3D print knit structures. Whilst Davis' project successfully makes use of digitally modelled linear loops to create a printed textile-based structure that has the ability to compress and expand, a limitation of this research is the inadequate closed loop ends required for the 'fabric' to hang together. However, Davis' research does highlight that the clear rubber material chosen to print with can enable another dimension for mobility through elongation and stretch in the material.

More recently, Melnikova, Ehrmann, and Finsterbusch (2014) have explored the possibility of 3D printing continuous single-face weft knitted structures with different polymer materials. A limitation of this research is poor print resolution when printing at small scale and limited flexibility.

2.3. Process

3D printing technologies and the materials available to print with have developed over the past 10 years. The two main types of process that have been used to create textile-based structures to date are Fused Deposition Modelling (FDM) and selective laser sintering (SLS).

2.4. Fused deposition modelling (FDM)

FDM technology uses a heated nozzle to deposit layers of melted plastic layer by layer. Advantages of this technology are that it is relatively cheap and simple shapes require no support material, however, complex geometries such as interlinking structures require a second nozzle to deposit a support material that can either be dissolved or cut away after printing. Recently published research (Melnikova et al., 2014) shows the possibility of 3D printing single-face weft knitted structures by FDM however, a limitation of the research is that the support structures required are too fine to print resulting in limited success when printing the structures at small scale.

Partsch, Vassiliadis, and Papageorgas (2015) have explored FDM to 3D print 'woven' fabric at various resolutions to explore flexibility and shearing capability. A limitation of this research is the poor print quality resulting in limited flexibility.

2.5. Selective laser sintering (SLS)

In the SLS process, a carbon dioxide (CO_2) laser is used to fuse fine powder into solid material. The laser is directed by a computer guided mirror and builds objects in layers of 0.1 mm, the building platform lowers down by this measurement each time allowing the next layer of powder to be rolled onto the surface. The non-sintered powder acts as a support material for the build object. The excess powder is then removed by high pressure after printing. This process has the advantage of being able to print complex geometries without the use of additional support material making it an ideal method to explore fine interlinking textile-based structures.

2.6. Material

As 3D printing is an emerging technology, the range of materials available to print which is constantly evolving.

2.7. FDM printers

FDM printers use a variety of thermoplastics to print with, these include acrylonitrile–butadiene-styrene (ABS) and biopolymer polylactic acid (PLA).

ABS: ABS material properties include toughness and ductility making it a suitable material for FDM nozzle extrusion. ABS is around one-third cheaper than other thermoplastic such as polyamide (PA, Nylon). Examples of textile-based structures printed using ABS include Danit Peleg's (2015) fashion collection. Whilst Peleg's pieces demonstrate some flexibility the ABS material is limited in how fine the structures can be printed and the quality of the material deposition due to nozzle extrusion is rough.

PLA: Melnikova et al. (2014) have used PLA material to print single-face weft knitted structures. Whilst the material does exhibit some flexibility there are 'fine undesirable connections between stitches' (Melnikova et al., 2014) a result of the FDM nozzle extrusion.

2.8. SLS printers

The SLS process is compatible with a variety of Nylon based powders. Nylon is a popular engineering thermoplastic due to its lightweight, strong and flexible properties because of this it has been used by numerous designers to successfully print articulating structures.*Nylon:* Nylon 12 (PA12) in particular has outstanding mechanical properties including low moisture absorption, good dimensional stability and superior flexibility. The Nylon 12 3D printed bikini developed by Continuum Fashion makes use of thousands of SLS Nylon circular components interconnected by thin spring like structures allowing the piece to hold its form whilst still being flexible. More recent examples include three ASFOUR's collaboration with Bradley Rothenberg to create a Spring/Summer 2016 dress in which SLS Nylon 12 is used to create incredibly fine interlocking lattice structures.

Alongside Nylon based powders the SLS process is compatible with certain polyurethane plastics including thermoplastic polyurethane (TPU).

TPU: TPU belongs to a group of rubber like plastics called thermoplastic elastomers (TPEs). TPU material properties include elasticity and moderate strength. TPU has been used by designers most notably Iris van Herpen & Julia Koerner to 3D print a dress that explores flexibility through an inter-woven thread like structure.

2.9. Summary

The literature has revealed that the area of 3D printed textiles is an emerging field with an increasing number of practices exploring the possibility of printing flexible textile-based structures. The literature has highlighted that the majority of the research to date makes use of multiple assemblies to enable movement through linked or hinged rigid parts. Research exploring 3D printed continuous geometry is less available and published work exploring the knitted structure as a form of continuous geometry is extremely under developed.

The aim of this study is to address this gap in knowledge by exploring the 'continuous fibre type geometry' (Crookston et al., 2007) of 3D printed knit-based structures and evaluate their material performance. The originality of the research lies in applying a textile understanding of knit's continuous inter-looping structures and inherent stretch properties to test both single-face (plain) and double-face (interlock) weft knitted structures for their extensibility and flexibility.

3. Method

The testing of 3D printed textile structures is still in its infancy, as such the design of this study is exploratory. The 3D printed knit structures are tested using compression, extension, stretching and folding to gain quantitative data in relation to their material performance. The data collection is then analysed and the experimental results are discussed in relation to potential application across the textiles sector.

3.1. Materials

The literature review has identified SLS as the most suitable technology for this research project to provide the highest print resolution. The 3D printed knit structures for this study were printed using an EOS Formiga P1 machine. These machines are calibrated up to ±0.15% on the X and Y-axis and build with 0.1 mm layers on the Z-axis. As the machine builds using fine layers of powder the software EOS RP tools was used to slice the 3D CAD data into layers.

Nylon (PA12) was selected as the material for the study as it requires no support structures and has inherent material properties including good dimensional stability and superior flexibility. These attributes are key when testing stretch behaviour and flexibility. A critical issue relating to the quality of Nylon SLS is the powder ratio used. The material for commercial Nylon SLS prints is a blend of new and recycled powder. This is due to maintaining cost efficiency. Machine manufacturers EOS recommend a powder ratio of 1:1 to achieve the best part quality and material performance.

London based 3D print bureau Digits 2 Widgets were chosen to print the pieces due to their commitment to producing Nylon SLS at its optimum quality whilst exploring the boundaries of the technology's capabilities. Digits 2 Widgets guarantee the optimum 1:1 new to used powder by housing a proprietary mixing unit that simultaneously mixes and transports the powder directly to the machines.

3.2. 3D CAD development

In order to 3D print knit-based structures a 3D CAD drawing is required. This CAD drawing needs to consider the pipe wall thickness and distance between objects, particularly when creating inter-looping structures such as knitting. To begin the process a CAD drawing of the plain knit structure was created. Digits2Widgets' in house CAD designer Tom Mallinson was identified as having the required CAD modelling skills to translate the knit patterns into three dimensions and then manipulate them to the configurations of interest. His previous experience producing Digits2Widgets' own chainmail based 'fabrics' meant that he had the expertise to understand the material limitations and tolerances that these experiments could be successfully taken to.

McNeel Rhinoceros (Rhino) software was chosen to generate the 3D CAD models due to its powerful modelling capabilities. A single knit loop unit was initially drawn as curves. Once created this loop unit was repeated and arranged using the array command to create the desired width (courses) and length (wales). To create the tubular structures the flow along curve command in Rhino was used specifying the diameter of the tube and the length required to flow along (Figure 1). This line drawn tube was then piped with specified wall thickness. Once piped, these designs were run through the Magics 3D printing software to make sure all neighbouring and intersecting parts have a distance of at least 0.4 mm.

In order to be most cost efficient a size 6 SLS Nylon container (180 mm × 220 mm × 50 mm) was chosen from the Digits 2 Widgets website (www.digits2widgets.com) to print the pieces, this determined the maximum printed length and diameters of the tubes for both the plain knit and interlock structures. The size 6 container allowed for five tubes to be printed next to each other.

3.3. Sample testing

Once printed each of the tubes were tested to determine their compressed and extended length, this was achieved by compressing each of the tubes by hand to the minimum length without deformation of the loops and recording the measurement. Each tube was then extended by hand to the maximum length without deformation of the loops this measurement was then recorded. Following this, each tube was tested for stretch capability by manually stretching each tube over a cardboard cone structure with a minimum diameter of 25 cm and a maximum diameter of 55 cm. The stretching over the cone was repeated 10 times to test stretch and recovery properties of each tube. Finally, each tube was manually manipulated by bending and folding by hand to test for overall flexibility and ability to return back to original form.

4. Results and discussion

4.1. Single-face (plain) weft knitted structures

Tubes A, B, C are single-face weft knitted tubular structures printed at decreasing loop size and pipe wall thickness. Table 1 records the results of the testing methods. Figures 1, 2, and 3 show each of the tubes compressed, extended, stretched over the cone form and manually bent and folded by hand (the photographs show the tubes compressed and extended without any external force acting upon them).

As shown in Table 1, Tube A has a vertical compression and extension range of 95 mm (52.8%). Figure 1 illustrates that Tube A was easily able to be stretched horizontally across the courses of the knit structure to cover the cone structure. This demonstrates that a pipe thickness of 1.42 mm is strong and flexible enough for

Table 1. Results of testing single-face (plain) weft knitted tubular structures.

Variables	Tube type		
	Tube A	Tube B	Tube C
Pipe wall thickness (mm)	1.42	0.94	0.64
Internal diameter (mm)	31.86	29.01	15.13
Loop height (mm)	21.11	8.73	5.51
Loop width (mm)	9.43	5.56	3.26
Resting length (mm)	180	180	180
Compressed length (mm)	150	155	155
Decrease (mm)	30	25	25
Decrease (%)	16.7	13.9	13.9
Extended length (mm)	245	235	220
Increase (mm)	65	55	40
Increase (%)	36.1	30.6	22.2
Stretched diameter	55 mm	55 mm	N/A
Loop recovery (×10)	Yes	yes	no
Folded height (mm)	65	40	20
Folded width (mm)	75	65	60

Note: Decrease and increase amounts calculated from starting resting length.

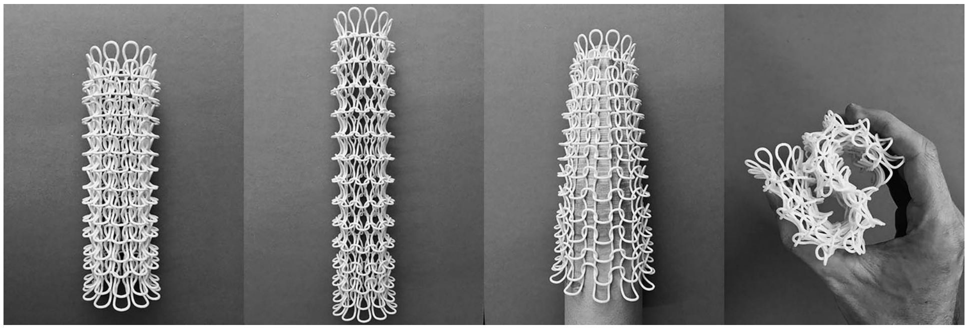

Figure 1. Tube A: compressed, extended, stretched and folded.

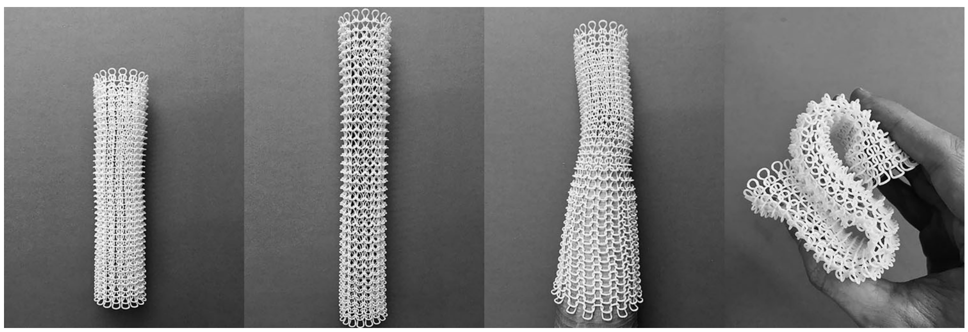

Figure 2. Tube B: compressed, extended, stretched and folded.

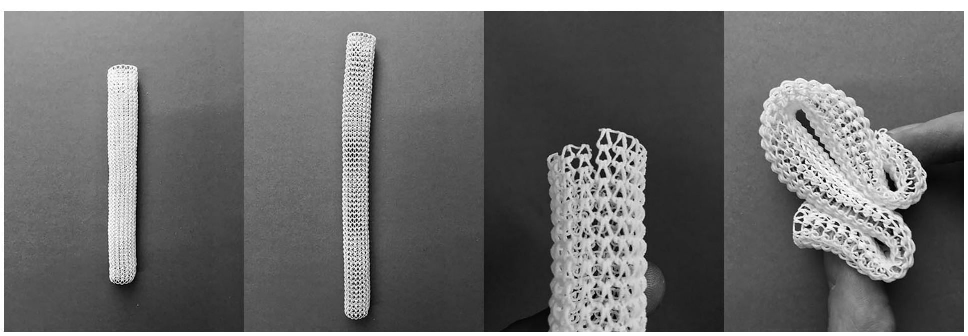

Figure 3. Tube C: compressed, extended, broken loop (detail) and folded.

the loops to expand. When stretched to the maximum cone diameter of 55 cm, Tube A exhibits some loop deformation however, the loop structure recovers even after repeated stretching (10 times). Tube A can be manually bent and folded by hand and returns back to original form.

Table 1 shows that Tube B has a vertical compression and extension range of 80 mm (44.4%). Figure 2 illustrates that Tube B was able to be stretched horizontally across the courses of the knit structure to cover the cone, demonstrating that a pipe thickness of 0.94 mm is strong and flexible enough for the loops to expand however, there was more material resistance than with Tube A. When stretched to the maximum cone diameter of 55 cm, Tube B exhibits greater loop deformation than Tube A however, the loop structure recovers even after repeated stretching (10 times). Tube B can be manually bent and folded by hand and returns back to original form.

Table 1. shows that Tube C was able to extend vertically by 65 mm this in an increase of 41.9%. Figure 3 illustrates that Tube C was unable to be stretched over the cone, attempts to stretch the tube horizontally across the courses of the knit structure result in the loops breaking, this demonstrates that the pipe thickness of the loops (0.64 mm) is too fine to allow for flexibility. However, this tube does still demonstrate great flexibility when bending and folding by hand and does return to the original form.

4.2. Double-face weft knitted structures (interlock)

Tubes D and E are double-face weft knit tubular structures printed at decreasing loop size and pipe wall thickness. Table 2 records the results of the testing methods. Figures 4 and 5 show each of the tubes compressed, extended, stretched over the cone form and manually bent and folded by hand (the photographs show the tubes compressed and extended without any external force acting upon them).

As shown in Table 2, Tube D has a vertical compression and extension range of 77 mm (42.8%). Figure 4 illustrates that Tube D was easily able to be stretched horizontally across the courses of the knit structure to cover the cone structure. This demonstrates that a pipe thickness of 0.94 mm is strong and flexible enough for the loops to expand. When stretched to the maximum cone diameter of 55 cm, Tube D exhibits slight loop deformation, however, the loop structure recovers even after repeated stretching (10 times). Tube D can be manually bent and folded by hand and returns back to original form.

Table 2. Results of testing double-face (interlock) weft knitted tubular structures.

Variables	Tube type Tube D	Tube E
Pipe wall thickness (mm)	0.94	0.92
Internal diameter (mm)	32.10	29.54
Loop height (mm)	13.67	9.14
Loop width (mm)	5.73	5.65
Resting length (mm)	180	180
Compressed length (mm)	155	155
Decrease (mm)	25	25
Decrease (%)	13.9	13.9
Extended length (mm)	232	234
Increase (mm)	52	54
Increase (%)	28.9	30.0
Stretched diameter	55 mm	55 mm
Folded height	60 mm	45 mm
Folded width	75 mm	65 mm

Note: Decrease and increase amounts calculated from starting resting length.

Table 2 shows that Tube E has a vertical compression and extension range of 79 mm (43.9%). Figure 5 illustrates that Tube E was able to be stretched horizontally across the courses of the knit structure to cover the cone, demonstrating that a pipe thickness of 0.92 mm is strong and flexible enough for the loops to expand however, there was more material resistance than previous Tube D. When stretched to the maximum cone diameter of 55 cm, Tube E exhibits greater loop deformation than Tube D however, the loop structure recovers even after repeated stretching (10 times). Tube E can be manually bent and folded by hand and returns back to original form.

Traditional plain knitted structures are extensible in both the lateral and longitudinal directions. The lateral extension is greater than the longitudinal extension as a loop pulled in the lateral (widthwise) direction can extend by its entire length. The experimental results have shown that all of the printed structures (A, B, C,

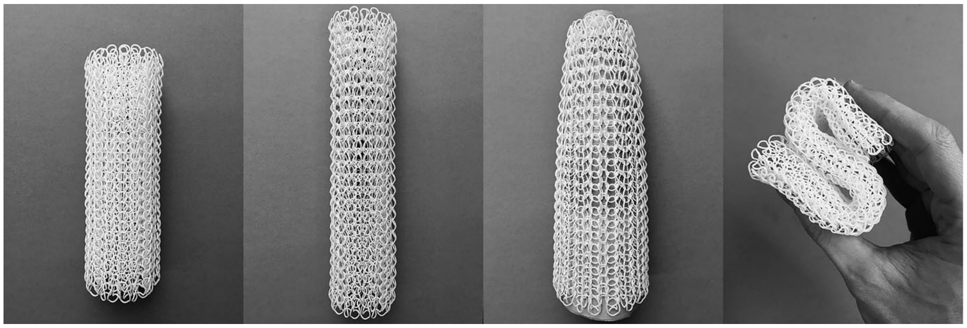

Figure 4. Tube D: compressed, extended, stretched and folded.

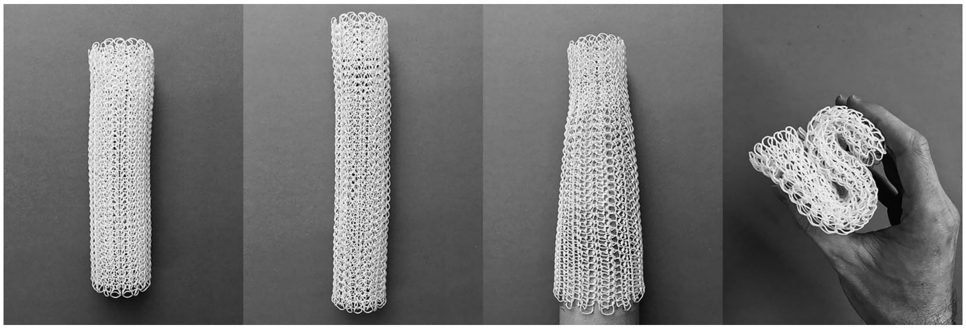

Figure 5. Tube E: compressed, extended, stretched and folded.

D, E) demonstrate the ability to compress and extend longitudinally within the length of the knitted loop structure (wales). Structures A, B, D and E all exhibit the ability to be stretched laterally to cover the cone with a maximum diameter of 55 mm, this is due to the pipe wall thicknesses and loop structure allowing for elongation across the courses. Due to the fineness of the pipe wall thickness Tube C is unable to be stretched horizontally as the loops begin to break. These results extend the findings of Melnikova et al. (2014) who produced SLS single-face weft knitted structures at 0.8 mm material thickness with limited flexibility. After being removed from the cone structures A, B, D and E demonstrate the ability to recover and return to original form, this can be attributed to loop structure providing elasticity (ie stretch and recovery) in combination with the flexibility and material memory of the Nylon (PA12) material used to print with.

5. Conclusion

The aim of this study was to evaluate the material performance of SLS Nylon (PA12) 3D printed knit structures. To do this both single-face (plain) and double-face (interlock) weft knitted structures were tested to record their compression, extension, stretch and flexibility. This study has shown that it is possible to 3D print tubular knit-based structures that exhibit the stretch and extensibility of traditional knitted textile structures along with the mechanical properties of the material used. However, a limitation of this research is the lack of standards or defined test procedures suitable for testing 3D printed textile-based structures. The author is planning to carry out further research to test the durability of these printed structures in a controlled laboratory environment to test tensile strength, elongation and load to the breaking point.

This research has shown that SLS is a suitable manufacturing process to achieve flexible tubular knit-based structures using Nylon (PA12) powder. Further research into other flexible powder material such as TPU would be of interest to test the mechanical behaviour of the material, in combination with the knitted structure's inherent properties of stretch and flexibility. This would enable a comparative study to be made between Nylon (PA12) and TPU.

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